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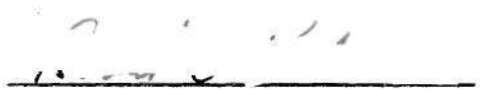

THE INFLUENCE OF OFF-RAMP SPACING ON THE OPERATING CHARACTERISTICS OF THE ATLANTA NORTH FREEWAY

A THESIS

Presented to

The Faculty of the Graduate Division

by

Robert Cleophus Kirk

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THE INFLUENCE OF OFF-RAMP SPACING ON THE OPERATING CHARACTERISTICS OF THE ATLANTA NORTH FREEWAY

Approved:

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SUMMARY

The spacing of interchanges on freeways can have a pronounced effect on the efficiency of operation of a freeway in a downtown area and can therefore affect the entire transportation system within the city. The proper spacing of interchanges on freeways is also important from a cost viewpoint and from a vehicle-time viewpoint. The purpose of this study was to determine the influence of off-ramp spacing on the operation characteristics of the Atlanta North Freeway.

In making this study, data were used from a ramp spacing study being conducted by the Engineering Experiment Station, Georgia Institute of Technology. In this study the southbound off-ramps at Fourteenth Street, Tenth Street, and North Avenue were closed for a period of two weeks each during the morning peak traffic period. Volume, speed, and density data were collected at four study locations along the North Freeway during each ramp closure and during normal operation of the Freeway. These data were collected by the use of time-lapse movie photography at Fourteenth Street, Tenth Street, Fifth Street, and North Avenue.

Speed and delay studies were also made on the Freeway during each ramp closure and during normal operation. The total overall travel time in vehicle-minutes and the total overall travel distance in vehicle-miles were computed for all vehicles using the North Freeway between 7:40 A. M. and 8:40 A. M.

An analysis of variance investigation was made on the data collected and the conclusions reached indicated the following:

1. Closing any one of the southbound off-ramps during the morning peak hour caused little or no improvement in the operating characteristics of the North Freeway. When an appreciable change was noted, it was usually a reduction in the quality of traffic flow.

2. In order for a freeway to efficiently handle the morning peak hour traffic flow into the central city, the off-ramps should be spaced as closely as possible, consistant with design factors and the ability of the surface street system in the vicinity of the off-ramp to accommodate the traffic flow from the ramp.

3. The total overall vehicle-minutes of travel time used by all the vehicles traveling through the freeway system is an effective measure of the level of service existing in a freeway system.

As a result of this study, it is recommended that deceleration lanes be constructed at all southbound off-ramps on the Atlanta North Freeway. It is also recommended that further studies be conducted to determine the feasibility of the construction of a southbound off-ramp at Fifth Street, which is presently a grade separation only.

CHAPTER I

INTRODUCTION

The location and spacing of interchanges on a freeway may have a decided effect on the effective operation of the freeway. Because freeways are an important part of the overall transportation system of a city, the location and spacing of interchanges may influence the efficient operation of the entire street system of the city.

In a freeway system interchanges which are spaced too far apart may not permit the full potential use of the system and thus not provide the necessary service for which the freeway was designed. Interchanges which are spaced too close together can result in inefficienty and a possible loss of capacity of the freeway. Studies indicate that the factors which have the greatest effect on the freeways are the design of the ramps and the operation of the interchanges (1)*.

It has been estimated that by the year 1980 there will be a need for some 16,000 miles of freeways to serve the traffic requirements of urban areas (2). One of the major costs of a freeway system is its interchanges. Since the cost of these interchanges is high, their spacing becomes obviously important from an economical point of view. If an interchange is constructed without proper economic justification, it will add unwarranted costs to the freeway construction. Also, the lack of an interchange at a required location can reduce the operation efficiency of

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*Numbers in parentheses refer to references listed in the Bibliography.

the entire freeway system and cause the addition of unnecessary travel time and travel distance to the motorist within the system.

Purpose

The purpose of this study is to determine the influence of off-ramp spacing on the operation characteristics of the Atlanta North Freeway. A comprehensive investigation was made of traffic volumes, speeds, and densities of the in-bound traffic during the morning peak hour on the Atlanta North Freeway under various ramp spacing conditions. Speed and delay studies were also conducted on the Freeway under similar conditions during the morning peak hour.

The data presented in this thesis were collected on a study being conducted by the Georgia Tech Engineering Experiment Station on Atlanta's Freeway System (3). Phase one of this study was conducted by Dr. Donald O. Covault and Robert R. Roberts during the afternoon peak traffic period and was concerned with on-ramp spacing. Phase two is concerned with the off-ramp spacing during the morning peak traffic period and is currently being conducted by Dr. Donald O. Covault and the author. In a study of this type, two different approaches could be used to gather information about the influence of ramp spacing on traffic in a freeway and its system of surface streets. One approach, utilizing the microscopic concept, would be a study confined to determining the influence of ramp spacing on the traffic flow characteristics on the freeway alone, disregarding the surface streets which serve the freeway. The second approach, utilizing the system concept, would be a study enlarged to consider the surface streets which serve the freeway as well. This method is known as the system concept (4).

The study by the Georgia Tech Engineering Experiment Station uses the system concept. This study will not consider the operation of the entire system, but will be concerned only with the operating characteristics of the Freeway.

Literature Research

Only limited studies have been made to determine the effect of varying ramp spacing on the operational characteristics of a freeway.

Studies have been made on the Gulf Freeway in Houston, Texas and on the Central Expressway in Dallas, Texas to determine the effect of eliminating the "short trip" from the freeways in the vicinity of the central business district (5). These studies were conducted by closing all the inbound on-ramps during the morning peak hour for a distance of approximately one and one-quarter miles from the central business district. These studies showed that volume control is feasible and practical in order to improve the operational characteristics on existing freeways (6). These studies further indicated that volume control measures of this type are necessary only for a period of about one hour during the peak traffic flow period.

A limited access facility to Lake Way, in Seattle, Washington, was controlled by the closure of three on-ramps during selected peak traffic periods (7). As a result of this study, the ramp closure operation data indicated that average speeds were increased by five miles per hour and there was a significant reduction in accidents.

Requirements for Interchange Spacing

There are two major factors which influence the location of interchanges on freeways. They are external factors such as size of city, type

of area and street pattern, and internal factors, such as the geometric features and operational characteristics of freeways (8).

External Factors

The need for closely spaced interchanges is reduced when the surface street pattern of the surrounding area is regular, such as the gridiron pattern. An irregular or hetrogeneous surface street pattern in the surrounding area may require closer spacing of interchanges because of increased difficulty in getting from the freeway to ones destination.

The location of interchanges is influenced considerably by the land use pattern in the vicinity of the freeway. Large industrial or commercial areas will usually require much more closely spaced interchanges than do remote residential areas.

One of the most important factors of ramp spacing is that of balance between freeway and surface street service. If the interchanges are spaced too closely, short trips will be attracted to the freeway and this may cause congestion. If the interchanges are spaced too far apart, intermediate length trips will remain on the surface street system. This situation may cause undue congestion and delay on these streets. A proper balance between a freeway and its surrounding surface streets will permit both systems to operate at optimum efficiency.

Internal Factors

The internal factors which should be considered in the spacing of interchanges are geometric features and operational characteristics. The geometric features which should be considered in determining the proper spacing for ramps are proper marking and directional signing, properly designed acceleration and deceleration lanes, maneuver areas and weaving sections, and accident experience (9). Operational characteristics of a

freeway are governed mostly by the freeway's geometric features.

A freeway requires a sign system which provides easily understood directions for the motorist. These directions should be given sufficient advance warning so that the motorist will have time to react without causing danger to other motorists. Therefore, the space between ramps must be sufficient for the motorist to read, comprehend, and react to the sign's messages safely and without confusion.

Sufficient spacing must be maintained between ramps in order to accommodate the weaving which will occur by the motorist which are leaving or have entered the freeway. The absolute minimum spacing between interchanges with light to intermediate weaving volumes should be 1800 feet. The normal minimum spacing is approximately 2600 feet and the preferable minimum spacing should be 4200 feet (10).

Another factor which should be considered in the location of interchanges is traffic accidents. The major locations of accidents on freeways are the interchanges where vehicles merge with or diverge from the through traffic (11). Because of this, there is increased opportunity for accidents for each interchange placed on a freeway.

An economic factor which must be considered when locating interchanges is the benefit-cost ratio. Economic justification for the location of interchanges is usually accomplished by a benefit-cost ratio analysis. The Bureau of Public Roads, United States Department of Commerce, has certain requirements for the minimum spacing of interchanges. These requirements are given in the instructions for completing the estimate of cost for the Interstate Defense System of Highways in accordance with Section 104(b) 5, Title 23, U. S. Code, Highways, which states in part:

> It is important that interchanges be located so as to properly discharge and receive traffic from other Interstate and Federal-aid system routes, or major arterial highways or streets. It is equally important that they not be spaced so closely as either to unnecessairly increase the cost of the system or interfere with the freeflow and safety of traffic on the Interstate System.
>
> Interchanges within urban areas should not be spaced closer than an average of two miles, in the suburban sections of urban areas not closer than four miles, and in rural section average not closer than eight miles.
>
> Obviously, however, in consideration of the varying nature of the highway street or road systems with which the Interstate System must connect the spacings between individual adjacent interchanges must vary considerably. In urban areas the minimum distance between interchanges should not be less than one mile and in rural areas not less than three miles. Under normal circumstances the increased cost of construction resulting from the development of an interchange should have a net benefit-cost ratio of not less than 1.0.

The benefit-cost ratio alone should not be the sole justification for spacing of interchanges. Some interchanges could probably be justified by this criterion which would not be desirable because of other factors which have been previously discussed.

One of the best measures of efficient ramp spacing on a freeway is the total overall travel time of the vehicles in the system of surface streets and freeways (12). The total travel time in the system is the total amount of time that all the vehicles spend in the system during a specific period of time. This measure is usually expressed in vehicle-minutes.

The idea of the total overall travel time is to space interchanges such that the total travel of all the vehicles traveling on the freeway and surface streets within the system is minimized.

CHAPTER II

DATA COLLECTION

Study Site

The area in the vicinity of the North Freeway, as shown in Figures 1 and 2, comprises an area lying north of the Central Business District of Atlanta, Georgia.

The majority of vehicles which are in this area during the A. M. peak hour is traffic which is passing through the area, not traffic having a destination within the area. The land use in this study area consists mostly of small businesses, apartment houses, boarding houses, medium and small size hotels, old residences, service stations, and insurance offices.

The surface street system within this area consists of five arterials running generally in a north-south direction and three arterials running in an east-west direction. The North Freeway runs generally north-south approximately in the center of the study area. The southbound off-ramps from the North Freeway are located at Fourteenth Street, Tenth Street, and North Avenue. The junction of the Northeast and Northwest Freeways is 0.30 miles north of the Fourteenth Street interchange.

The interchanges on the North Freeway are located at Fourteenth Street, Tenth Street, and North Avenue. Each of these interchanges is a diamond type with the off-ramps leaving directly from the Freeway with no deceleration lanes provided. Fifth Street is a grade separation only, with no Freeway access provided. The Freeway was completed and opened to traffic from Peachtree Street to North Avenue in the spring of 1950. The design

speed used on the Freeway was 50 miles per hour with a ramp design speed of 35 miles per hour. The design hour volume was 1500 vehicles per lane per hour. The maximum vertical gradient used was five per cent and the maximum degree of horizontal curvature was three degrees.

The North Freeway consists of three 12 foot lanes in each direction of travel. The Northeast and Northwest Freeways each consist of two 12 foot lanes in each direction of travel. The Freeways and ramps were constructed of portland cement concrete and the surface of the ramps has been darkened to provide color contrast.

Procedure of Study

The ramp spacing was varied by closing certain ramps during the peak period of traffic flow. An interchange was effectively eliminated from the system when its off-ramp was closed and the spacings of the other interchanges within the system were changed. This method allowed the studies to be conducted without making permanent or semi-permanent changes in the Freeway.

The Southbound Off-Ramps at Fourteenth Street, Tenth Street, and North Avenue were closed during the morning peak period of traffic flow from 7:00 A. M. until 9:00 A. M., Monday through Friday, for a period of two weeks according to the following schedule:

Fourteenth Street Southbound Off-Ramp:	April 2 - 13, 1962
Tenth Street Southbound Off-Ramp:	April 23 - May 4, 1962
North Avenue Southbound Off-Ramp:	May 14 - 25, 1962

Each off-ramp was closed separately and only one ramp was closed at any one time. Table 1 shows the distance between interchanges for each

ramp closure and for normal operations.

The traffic was allowed to stabilize to permit the motorists to establish new travel patterns during the first week that each ramp was closed. Most of the studies were conducted during the second week of each ramp closure.

Figure 3 shows the method which was used in closing the ramps. Barricades were placed near the Freeway on the off-ramp so as to block the passage of vehicles on the ramp. In addition, signs were placed approximately 500 feet and 0.3 miles in advance of the ramp that was closed. These signs informed the motorists that the ramp was closed. The local newspapers, radio and television stations also aided in informing the public of the ramp closures.

Studies were made at four different locations along the Freeway. The four study locations were Fourteenth Street, Tenth Street, Fifth Street, and North Avenue. There are diamond interchanges at all the locations except Fifth Street which is a grade separation only. The studies were made under normal operation of the Freeway (no ramps closed), with the Fourteenth Street Southbound Off-Ramp closed, with the Tenth Street Southbound Off-Ramp closed, and with the North Avenue Southbound Off-Ramp closed. The data collected at these locations were the volume, speed, and density in each lane of the Freeway and the ramp volume. These data were collected between 7:20 A. M. and 8:00 A. M., and between 8:10 A. M. and 8:50 A. M. by the use of time-lapse movie photography. The cameras used in doing the filming held sufficient film for 40 minutes of continuous filming. Unloading and reloading the cameras necessitated the ten minute gap in the data collection from 8:00 A. M. to 8:10 A. M.

Table 1. Distance Between Interchanges in Miles

	Normal Operation (No Ramps Closed)	North Avenue Southbound Off-Ramp Closed	Tenth Street Southbound Off-Ramp Closed	Fourteenth Street Southbound Off-Ramp Closed
Peachtree Road				
	0.891	0.891	0.891	
Fourteenth Street				1.250
	0.359	0.359		
Tenth Street			1.067	
	0.708			0.708
North Avenue		0.897		
	0.089		0.089	0.089
Williams Street				

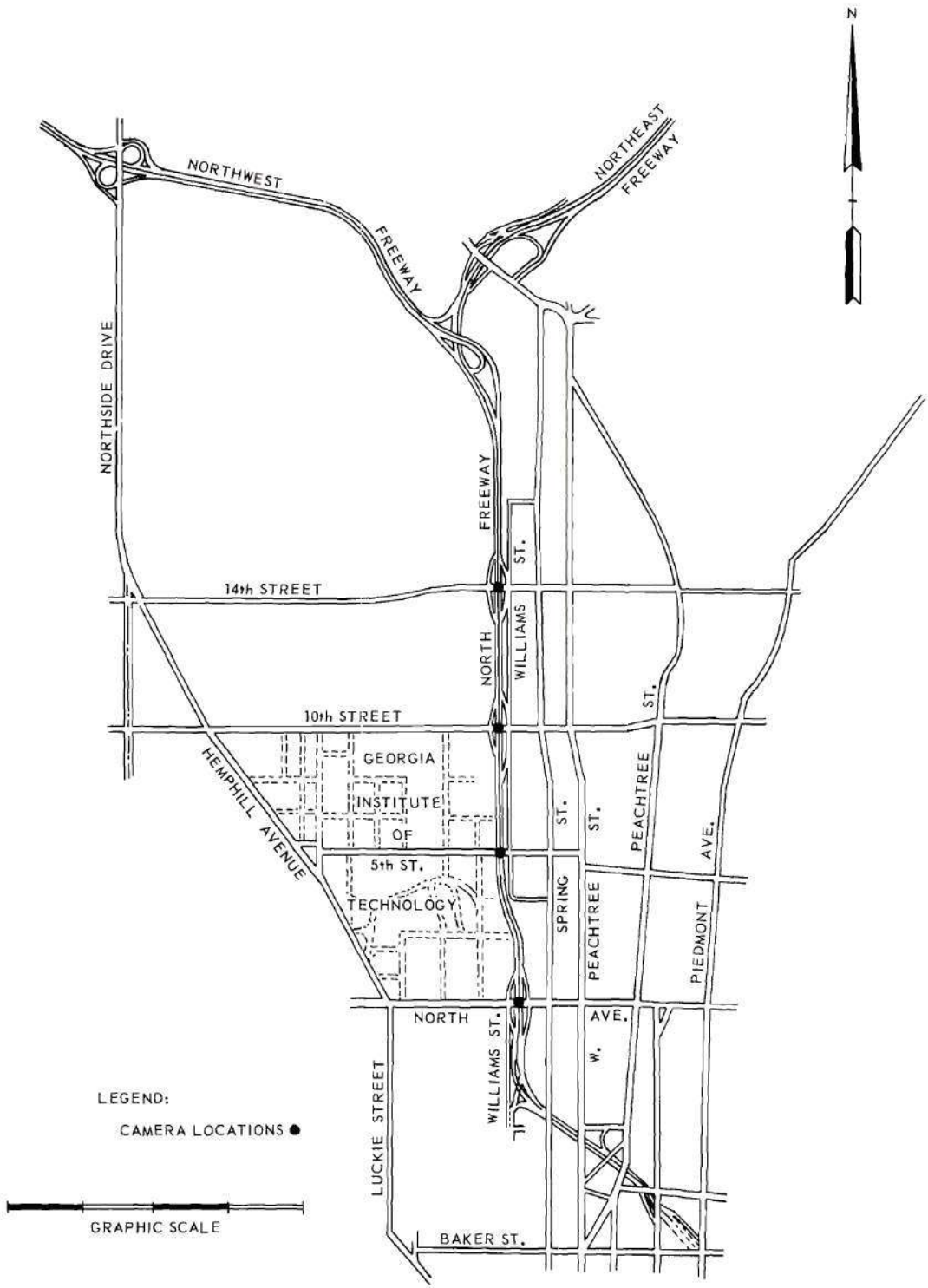

Figure 1. Street System in the Vicinity of North Freeway.

Speed and Delay Studies

An effective measure of the level of service which exists on a street is the overall travel time between two points on the street (13). The overall travel time along the Freeway was measured, using this principle, with speed and delay studies. The data which were gathered during each of these studies were total overall travel time, total running time (time that the vehicle was actually moving), total delay time and the cause of each delay, overall travel speed, and running speed (average speed while vehicle was actually moving). Travel time information was gathered for each 0.2 mile increment along the Freeway and then compiled between each pair of interchanges and for the entire Freeway length under consideration. The speed and delay study data were used in conjunction with the total hourly volume counts to obtain the total travel time in vehicle-minutes for all vehicles using the Freeway during each ramp condition. The total vehicle-miles of travel for all vehicles using the Freeway under each ramp condition was obtained by using the distance between interchanges and the total hourly volume counts.

Equipment and Instrumentation

Time-lapse movie photography was used to collect the data at the four study locations along the North Freeway. The motion picture cameras used for the time-lapse photography were Bolex 16 mm movie cameras driven by Bodine 110 volt AC synchronous motors as shown in Figure 4. The motors were geared to drive the cameras so as to film at the rate of 100 frames per minute. The cameras had a film capacity of 100 feet, or forty minutes at the rate mentioned above. The time interval between each frame exposure

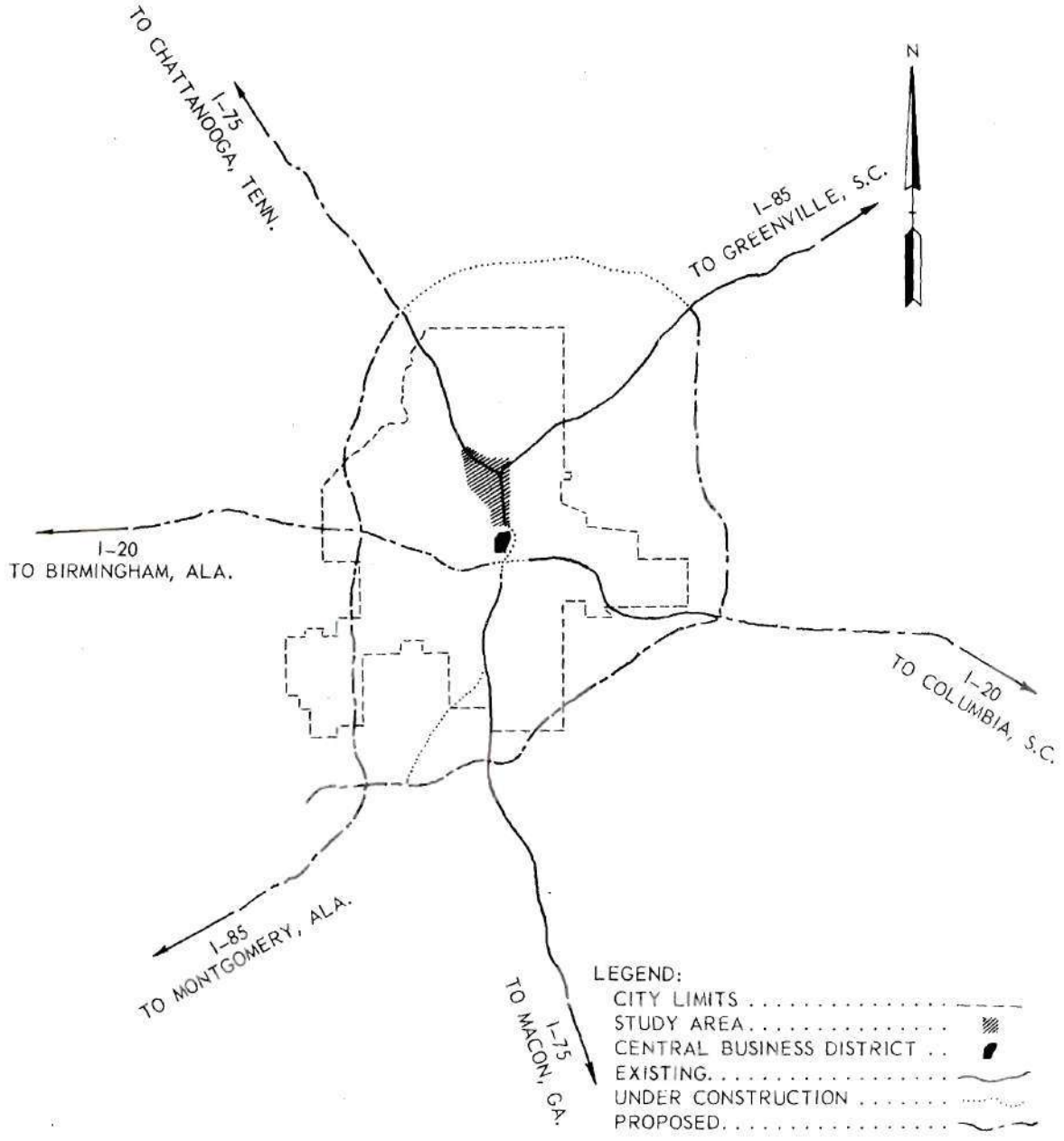

Figure 2. Atlanta Freeway System.

was 0.6 second. Synchronous motors were chosen to drive the camera since an accurate time interval was important. The shutter speed used was 1/15 of a second. This shutter speed was sufficiently fast to prevent blurring of the moving vehicle at the relatively slow speeds which occurred during the studies, but some blurring did occur when the vehicles were traveling at higher speeds.

A rubber clutch was used to connect the drive shaft from the motor to the camera as a safety device to prevent the camera from damage in the event the film jammed, thus locking the camera. The drive shaft was made in two parts which were connected by the rubber clutch which would slip rather than cause damage to the camera in the event of a film malfunction.

Color film was used for the photography whenever possible since it aided in the identification of vehicles. However, the use of high speed black and white film was used when necessary in several instances because of low light level.

A grid system was painted on the Freeway at each study location. Lines were painted at 50 foot intervals and perpendicular to the center-line of the Freeway. Figure 5 shows a typical grid system that was used in the study. Figure 6 shows a typical field location of a camera. The grid system may be seen on the Freeway in the background.

Film Analysis

The movie film was analyzed by projecting it through a time and motion study projector. The film could be studied one frame at a time or at a faster rate with this type projector.

The image was projected onto a screen with a grid reproduced on the

Figure 3. Method of Closing North Avenue Southbound Off-Ramp.

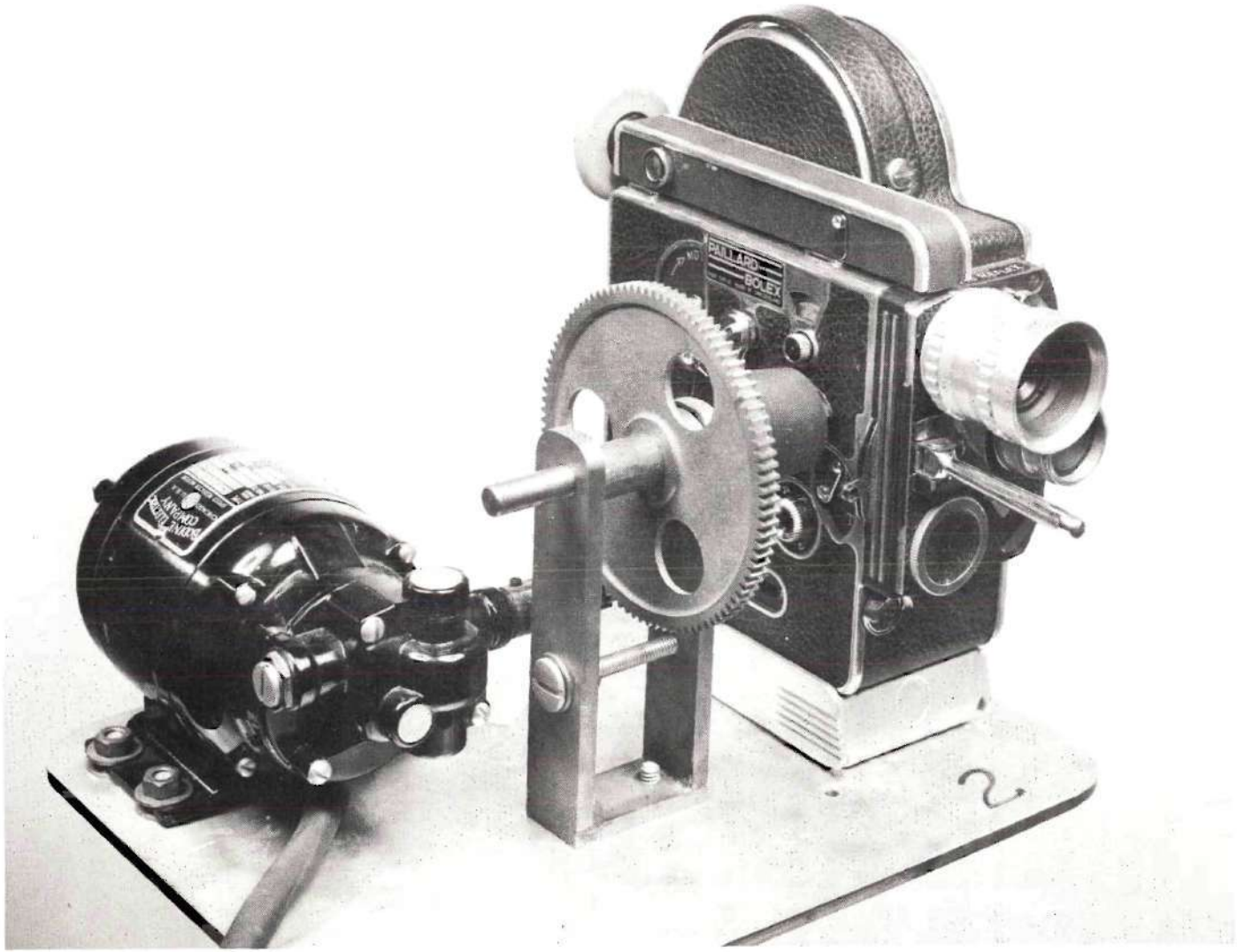

Figure 4. Time-Lapse Movie Camera Equipment.

screen which matched the grid painted on the Freeway. The vehicle speeds were obtained by measuring the distance the vehicle moved in relation to the grid system for a specific number of frames of film and dividing that distance by the time required for the vehicle to move between the number of frames being measured. Volume information was gathered by simply counting the vehicles as the film was run through the projector. The ramp volumes were also counted in this manner, but it was not possible to obtain the vehicle speeds on the ramps.

The above data were collected in five minute time increments. Each five minute time increment could be determined by counting each 500 frames as they passed through the projector. The time and motion projector had a frame counter which aided in counting the frames.

The speed of each vehicle was not determined, instead a sample size of 20 vehicles were studied for each five minute time period. Statistical analysis indicated that this size sample was sufficient to yield the true average speed within two miles per hour 95 per cent of the time (14).

CHAPTER III

ANALYSIS OF DATA

Computation of Results

It was necessary to take the raw data such as vehicle volume and vehicle speeds from the film and refine these data to a more usable form in order to analyze the data which were obtained.

The movie data were summarize for five minute time periods. The average lane volume and the total volume were obtained after each ramp exit. The total volume before the ramp would be the total volume of the lanes after the ramp plus the total number of vehicles which left the Freeway at the ramp, and the average lane volume would be this total volume divided by the number of lanes.

The speed in each lane was assumed to be the same immediately before and after the ramp exit since it was rarely observed that a vehicle slowed down because of other vehicles leaving the freeway at the ramp. The average weighted speed before and after the ramp exit was obtained by multiplying the volume in each lane by the corresponding average speed for that five minute period, adding these figures for all the lanes, and dividing the result by the total volume. It was assumed that all the vehicles leaving the Freeway exited from lane number one, the shoulder lane. The middle lane was designated as lane number two, and the median lane was designated as lane three. This lane numbering system is shown in Figure 5.

The basic factors of traffic flow are volume (V), which is defined as the number of vehicles which pass a point in a given period of time;

speed (S), expressed in miles per hour, and density (D), defined as the number of vehicles occupying a mile of roadway or lane at a given instant.

The volumes and speeds were obtained from the analysis of film. The density for each five minute interval was obtained by dividing the volume by the average speed for that interval. This gives the average density for a particular location for each five minute interval. The total volume on the Freeway was computed by adding the volumes in each of the three lanes for each time interval. The average lane volume, speed, and density were found by adding each of these factors over the three lanes and dividing each of these sums by three. This was done for each of the five minute time intervals.

In summary, the following information was evaluated from the time-lapse movie film:

1. Lane volume (before off-ramp)
2. Lane speed (before off-ramp)
3. Lane density (before off-ramp)
4. Total volume (before off-ramp)
5. Average lane volume (before off-ramp)
6. Average lane speed (before off-ramp)
7. Average lane density (before off-ramp)

The above data were observed or computed for each five minute time interval during the study period for each of four selected study locations. Figure 1 shows the study, or camera, locations. Ten five minute time intervals were used in this study from 7:40 A. M. to 8:40 A. M. Data were gathered from the film from 7:40 A. M. to 8:00 A. M. and from 8:10 A. M. to 8:40 A. M. These data were collected on two days during each of the ramp conditions at each of the four study locations.

The North Freeway was divided into a system of links in order to determine the total overall travel time and distance of all the vehicles on the Freeway. Each portion of the North Freeway between interchanges was designated as a separate link. This system of links is shown in Figure 7. The total overall travel time in vehicle minutes and total overall travel distance in vehicle-miles were computed for each of these links. The total overall travel time is shown in Table 29 and the total overall travel distance is shown in Table 31.

Analysis of Variance

An analysis of variance investigation allows data of the kind gathered in this study to be thoroughly analyzed. This type of analysis shows if there are interactions between pairs of factors or among any combinations of factors. Such an investigation further allows the conclusions drawn to be accompanied by statements of probability as to their correctness.

Mathematical models were formed in terms of the unknown parameters and the associated random variables in order to perform the analysis.

The dependent variables which were considered in this study were:

1. Volume
2. Speed
3. Density
4. Total travel time
5. Total travel distance
6. Overall running speed (not considering delays)
7. Overall travel speed (considering delays)

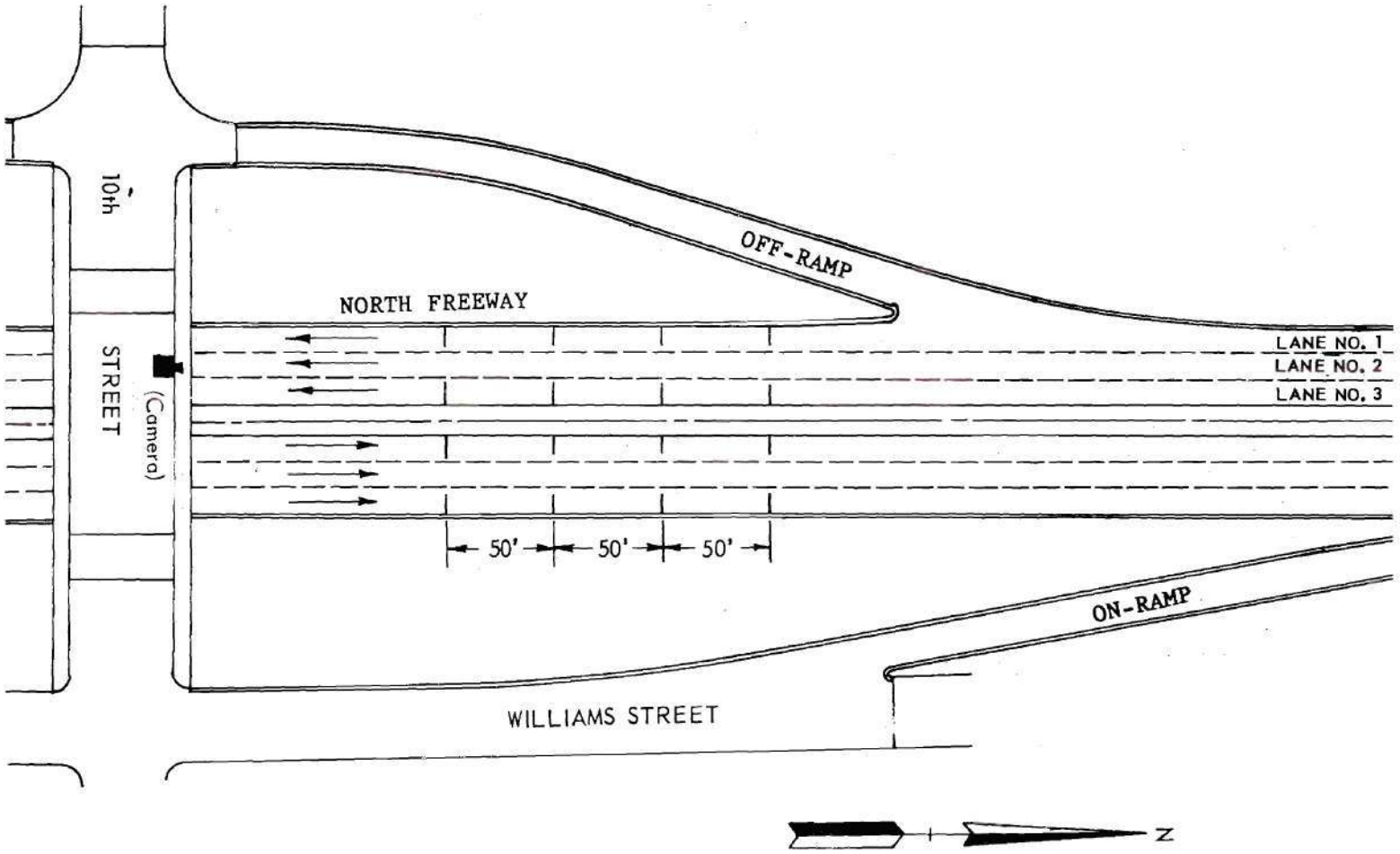

Figure 5. Layout of Typical Grid System.

The independent variables which were considered in this study were:

1. Ramp condition (Ramp which is closed)
2. Position (Observation point of Freeway)
3. Lane number
4. Day
5. Replication (Five minute time increment)

It was necessary to formulate two mathematical models in order to perform an analysis of variance investigation on each of the above mentioned dependent variables.

The mathematical model for the investigation of volume, speed, and density variables is as follows:

$$Y_{ijklm} = \mu + R_i + P_j + L_k + D_e + RP_{ij} + RL_{ik} + RD_{il} + PL_{jk}$$

$$+ PD_{je} + LD_{kl} + RPL_{ijk} + RPD_{ijl} + RLD_{ikl} + PLD_{jkl}$$

$$+ RDLD_{ijkl} + T_m(R_i\ P_j\ L_k\ D_e)$$

Table 2 shows the primary variables used in the above model. An individual observation of volume, speed, or density (Y_{ijklm}) on the Freeway located at the j^{th} position in the k^{th} lane, on the 1^{th} day, under the i^{th} ramp condition, in the m^{th} replication, has an expected value μ plus the sum of any main and interaction effects due to the independent variables.

The mathematical model for the investigation of total travel time, total travel distance, overall running speed, and overall travel speed is as follows:

$$Y_{ilm} = \mu + R_i + D_e + RD_{il} + T_m(R_i\ D_e)$$

Table 3 shows the primary variables used in the above model. An individual observation of total travel time, total travel distance, overall running speed, or overall travel speed (Y_{ie}) on the Freeway under the i^{th} ramp condition, on the 1^{th} day, in the m^{th} replication has an expected value (μ) plus the sum of any main and interaction effects due to the independent variables.

A level of significance was established in order to arrive at conclusions regarding the significance of any differences of the independent variables in these models. It was necessary to accompany conclusions with probability statements as to the correctness of the conclusion. The level of significance refers to the probability that one might conclude that real differences exist among the levels of an independent variable when actually only differences caused by chance fluctuations in the data exist. Mr. Darrell Huff says, "A difference is not a difference unless it makes a difference" (15). The 10 per cent level of significance was used in this study, meaning that the probability of concluding that there were real differences in the levels of the independent variables, when in reality there are no differences, is 0.10. The variables were also tested at the 20 per cent level, but only those interactions which were significantly different at the 10 per cent level were considered in this study.

Table 2. Primary Variables for Analysis of Variance of the Volume, Speed, and Density on the North Freeway

Factor	Abbreviation	Subscript	No. Levels	Factor Conditions
Ramp Condition	R	i	4	Fixed
Position	P	j	4	Fixed
Lane	L	k	3	Fixed
Day	D	l	2	Random
Replication	T	m	10	Random

Table 3. Primary Variables for Analysis of Variance of the Total Travel Time, Total Travel Distance, Overall Running Speed, and Overall Travel Speed on the North Freeway

Factor	Abbreviation	Subscript	No. Levels	Factor Conditions
Ramp Condition	R	i	4	Fixed
Day	D	l	3	Random
Replication	T	m	2	Random

CHAPTER IV

DISCUSSION OF RESULTS

The mathematical models used in analyzing the data collected in this study have been presented in Chapter III. The results of the analysis of variance investigation of these data are shown in Tables 33, 34, and 35. Each of these tables is the result of an analysis of 960 pieces of data. The data presented in these tables may be seen graphically in Figure 8. The data analyzed were volume, speed, and density on the Freeway for each five minute time interval from 7:40 A. M. to 8:00 A. M. and from 8:10 A. M. to 8:40 A. M. for each ramp condition, study location, lane, and day. Ramp condition refers to the ramp spacing which existed on the Freeway at the time the data were collected. The ramp conditions were determined by which of the ramps was closed during a particular time. The ramp spacing (ramp condition) was varied by closing no ramps (hereafter referred to as normal operation), by closing the Fourteenth Street Southbound Off-Ramp, by closing the Tenth Street Off-Ramp, or by closing the North Avenue Southbound Off-Ramp.

Multiple Range Tests

The analysis of variance investigation showed which of the interaction terms were significantly different but it did not show which level of the main effects caused the differences. It was possible to determine which level of the main effects caused the differences by using Duncan's Multiple Range and Multiple F tests (16). The variables were arranged in

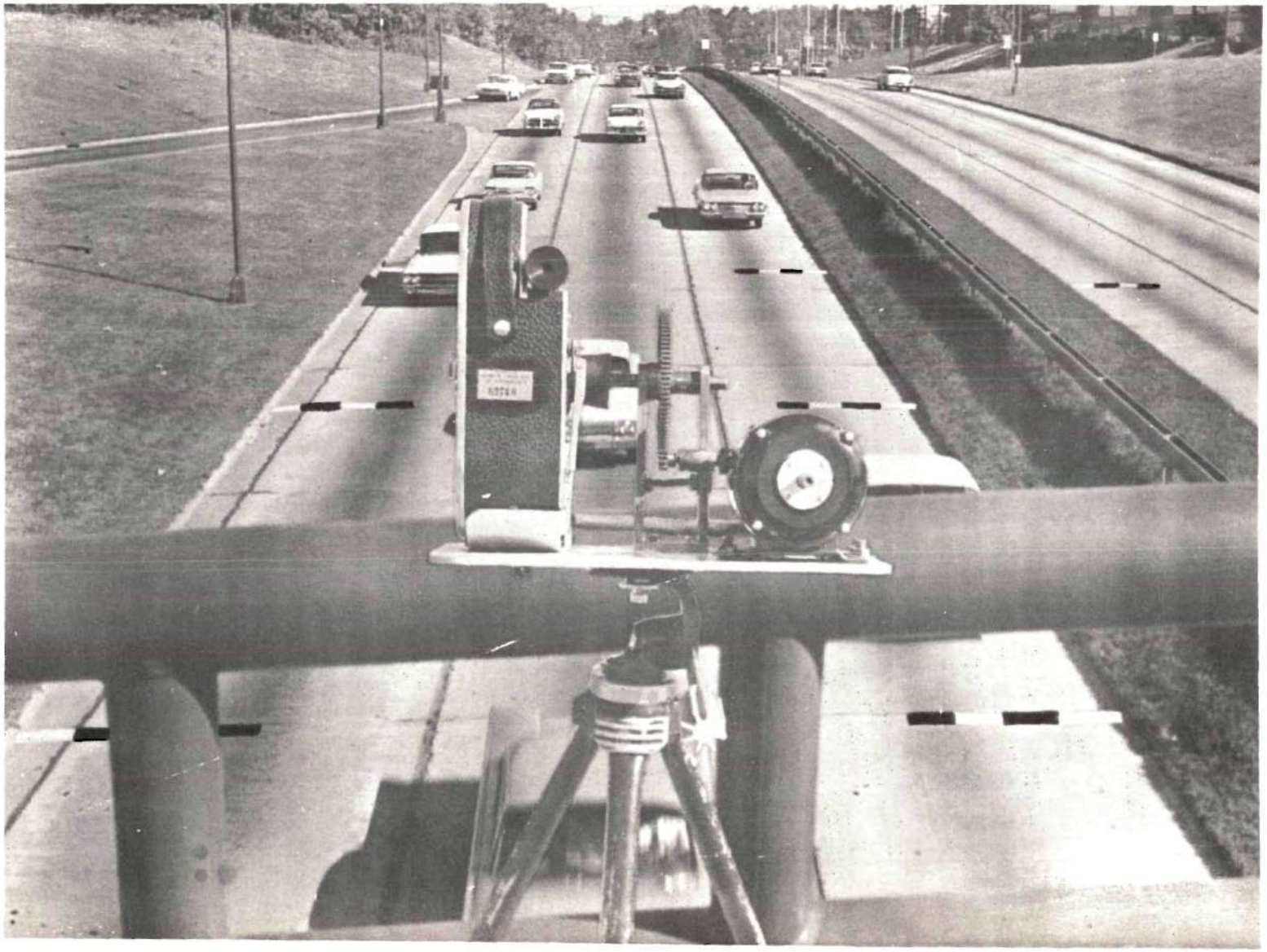

Figure 6. Field Location of Time-Lapse Movie Camera.

rank order from lowest values to highest values. Duncan's test was then applied to this arrangement and the factors were underscored where no differences were found. Those factors which are underlined together may be taken in any order since they are not significantly different, each from the other.

Level of Significance

The 10 and 20 per cent levels of significance were used for testing the variables in the analysis of variance of the data in this thesis. When a term or factor is called significantly different in this study, it is intended to mean a significant difference at approximately the 10 per cent level. The variables were tested at the 20 per cent level in order to determine at what level the variable may possibly become significant if it were not significant at the 10 per cent level. The variable was called significant in this study if the variable was significantly different at a level only slightly above the 10 per cent level.

Freeway Volumes

Volume Comparisions at Each Position Under Each Ramp Condition

Table 4 shows the rank order and significant differences of the volumes at the positions under each ramp condition. Table 5 shows the rank order and significant differences of the ramp conditions at each position. The study positions or ramp conditions are underlined where the differences in volumes are not significant and those study positions or ramp conditions which are underlined together have no significant differences. These relationships are shown graphically in Figure 8. For additional information on the volume data collected, see Table 22.

Table 33 shows the results of the analysis of variance investigation on the Freeway volumes.

Table 4. Rank Order of Freeway Volumes and Significant Differences of Study Positions

Ramp Condition	Lowest	2nd Lowest	2nd Highest	Highest
Normal Operation	5th Street	North Avenue	14th Street	10th Street
14th Street Closed	North Avenue	5th Street	10th Street	14th Street
10th Street Closed	North Avenue	10th Street	5th Street	14th Street
North Avenue Closed	North Avenue	5th Street	14th Street	10th Street

Table 5. Rank Order of Freeway Volumes and Significant Differences of Ramp Conditions

Study Location	Ramp Closed			
	Lowest	2nd Lowest	2nd Highest	Highest
14th Street	14th Street	Normal	10th Street	North Avenue
10th Street	10th Street	North Avenue	14th Street	Normal
5th Street	14th Street	North Avenue	Normal	10th Street
North Avenue	10th Street	14th Street	North Avenue	Normal

Volume Comparisons at Each Position Under All Ramp Conditions

When considering all of the ramp conditions together as shown in Figure 9, the volumes at Tenth Street and Fifth Street were not significantly different from each other. The rank order of the positions from lowest volume to highest volume were North Avenue, Tenth Street, Fifth Street, and Fourteenth Street.

Volume Comparisons Under Each Ramp Condition at All Positions

When considering all of the positions together as shown in Figure 9, the volumes with any one of the three off-ramps closed were not significantly different from each other, but all were different from normal operation. The rank order from lowest volume to highest volume was Fourteenth Street Off-Ramp closed, North Avenue Off-Ramp closed, Tenth Street Off-Ramp closed, and normal operation.

Lane Usage at a Non-Interchange Location

Table 6 shows the rank order and significant differences of the lane volumes which occurred at Fifth Street. Again, those ramp conditions which are underlined together have differences which are insignificant and they may be ranked in any order. Figure 12 shows the average values of the lane volumes which occurred at Fifth Street.

Lane Usage at Interchange Locations

Studying the volume conditions which existed at Fourteenth Street, Tenth Street and North Avenue as shown in Figures 10, 11, and 13 will give an indication of the effect of ramp closures on volumes at interchange locations. Tables 7, 8, and 9 show the rank order and significant differences of ramp conditions for each lane at Fourteenth Street, Tenth Street and North Avenue respectively.

Table 6. Rank Order of Freeway Lane Volumes and Significant Differences of Ramp Conditions at Fifth Street

Lane	Ramp Closed			
	Lowest	2nd Lowest	2nd Highest	Highest
1	North Avenue	14th Street	Normal	10th Street
2	14th Street	Normal	North Avenue	10th Street
3	14th Street	North Avenue	Normal	10th Street

Table 7. Rank Order of Freeway Lane Volumes and Significant Differences of Ramp Conditions at Fourteenth Street

Lane	Ramp Closed			
	Lowest	2nd Lowest	2nd Highest	Highest
1	Normal	14th Street	10th Street	North Avenue
2	North Avenue	14th Street	10th Street	Normal
3	North Avenue	14th Street	10th Street	Normal

Table 8. Rank Order of Freeway Lane Volumes and Significant Differences of Ramp Conditions at Tenth Street

Lane	Ramp Closed			
	Lowest	2nd Lowest	2nd Highest	Highest
1	10th Street	North Avenue	Normal	14th Street
2	14th Street	North Avenue	10th Street	Normal
3	North Avenue	10th Street	14th Street	Normal

Table 9. Rank Order of Freeway Lane Volumes and Significant Differences of Ramp Conditions at North Avenue

Lane	Ramp Closed			
	Lowest	2nd Lowest	2nd Highest	Highest
1	10th Street	North Avenue	14th Street	Normal
2	Normal	14th Street	10th Street	North Avenue
3	14th Street	North Avenue	10th Street	Normal

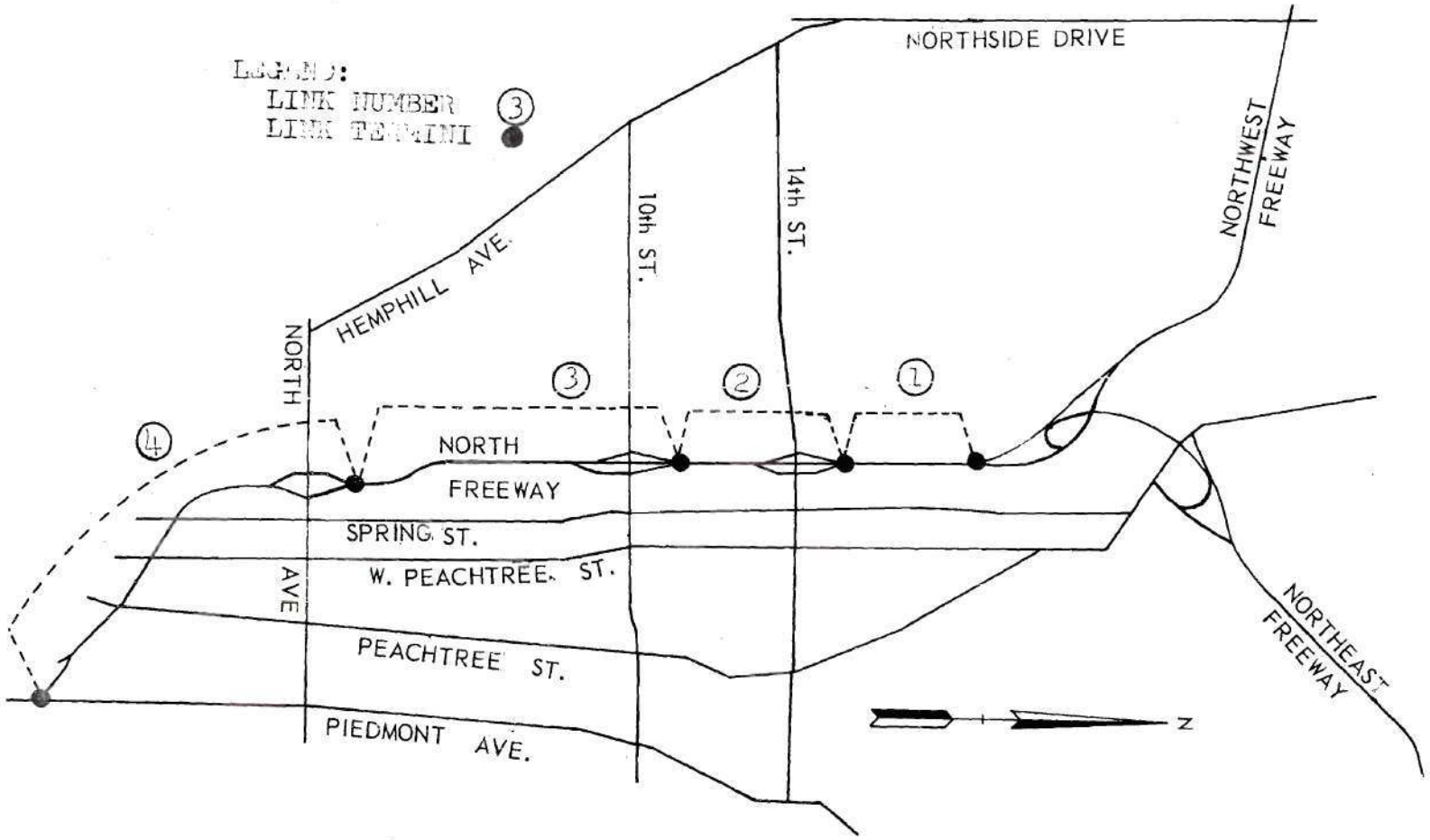

Figure 7. Network Links on North Freeway

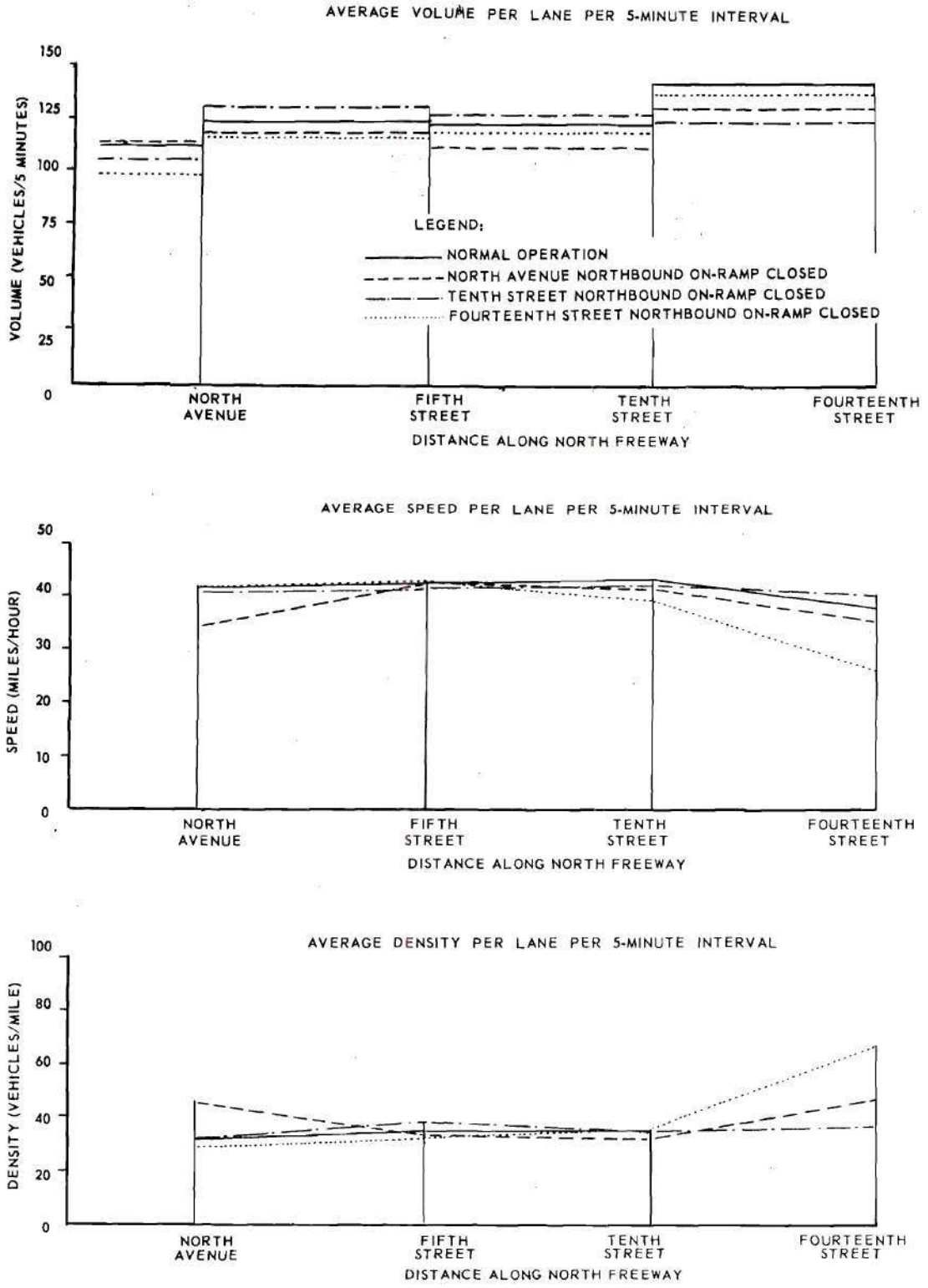

Figure 8. Average Volume, Speed, and Density Per Lane Per Five-Minute Time Interval on the North Freeway.

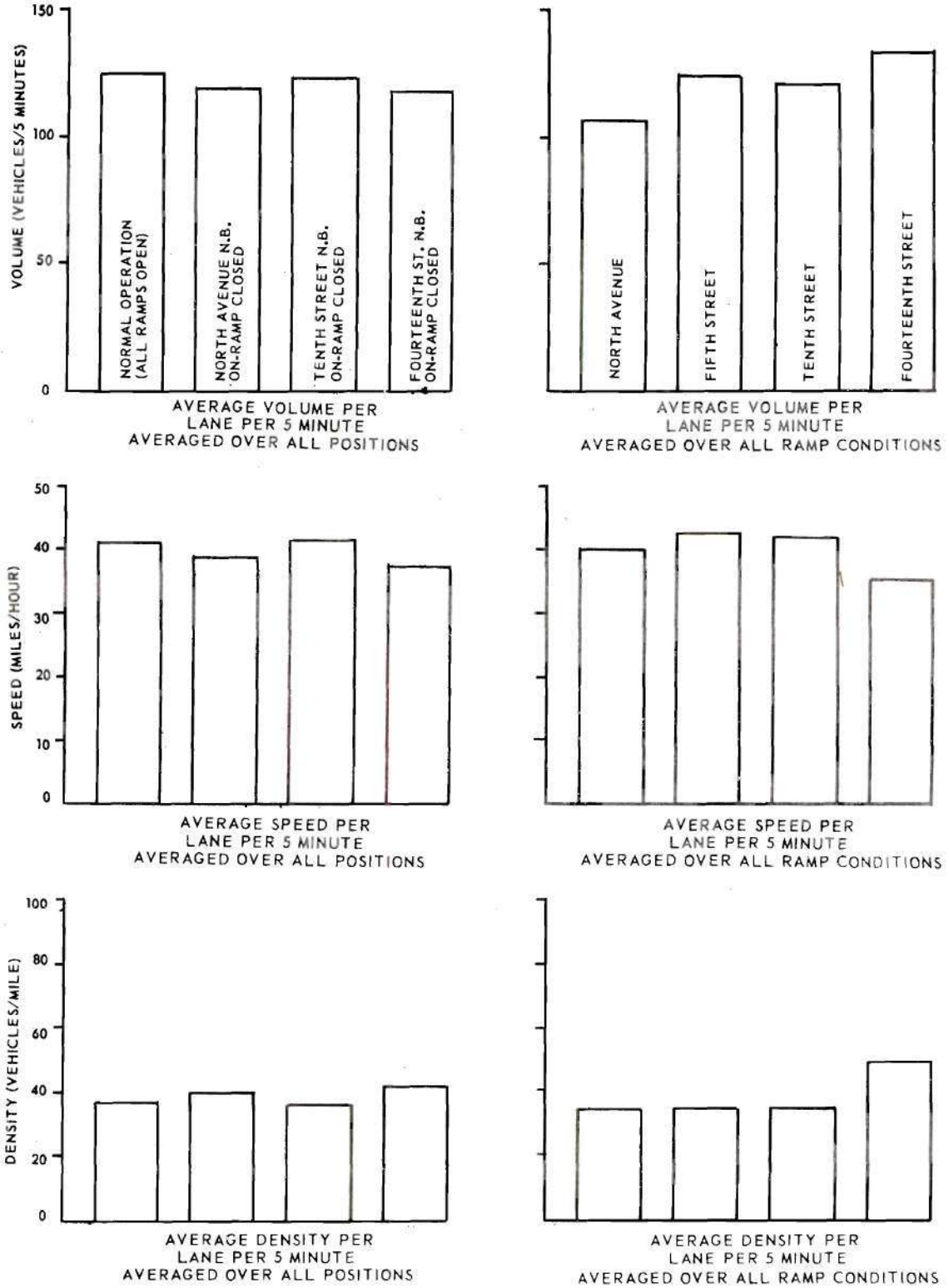

Figure 9. Average Volume, Speed, and Density Per Lane Per Five-Minute Time Interval on the North Freeway Considering All Positions and Ramp Conditions.

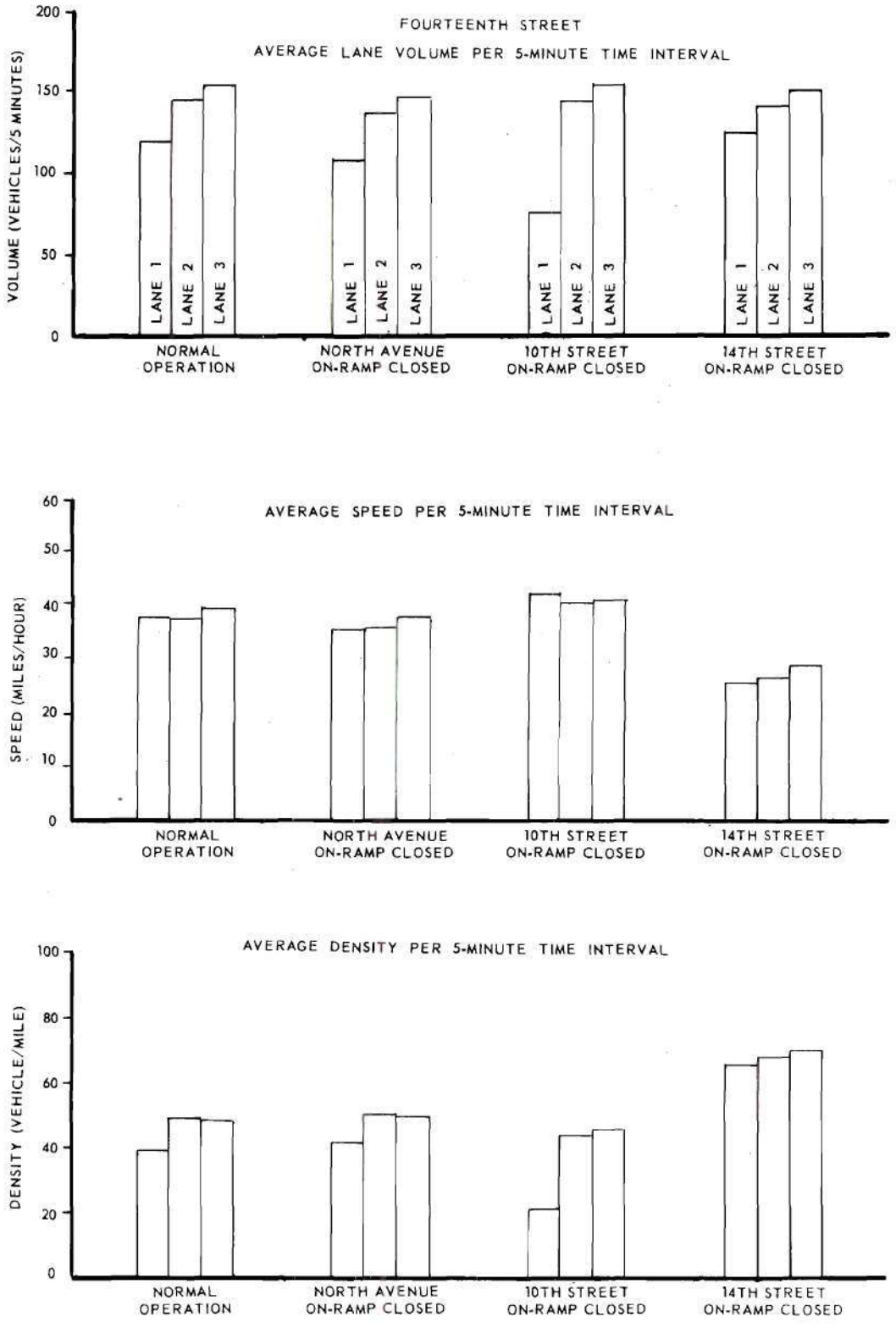

Figure 10. Average Lane Volume, Speed, and Density Per Five-Minute Time Interval on the North Freeway at Fourteenth Street.

Freeway Speeds

Speed Comparisons at Each Position Under Each Ramp Condition

The speeds which were obtained for each ramp condition and position are shown in Figures 8 and 9. One can see from these figures that there were insignificant differences in the speeds at any one of the study positions or under any of the ramp conditions except at Fourteenth Street with the Fourteenth Street Southbound Off-Ramp closed and at North Avenue with the North Avenue Southbound Off-Ramp closed. At each of these two above mentioned exceptions, the speeds were significantly less than the speeds which occurred under any other ramp condition as shown in Table 10. For additional information on the speed data collected, see Table 23.

Tables 10 and 11 shows the rank order and significant differences of the speeds at each of the study positions on the Freeway under each ramp condition. These data tend to indicate that the speeds on the Freeway are highest when the Freeway is operating normally with no off-ramps closed but there tended to be no significant differences in the Freeway speeds whether or not a ramp was closed.

For additional information on the speed data collected, see Table 23. Table 34 shows the results of the analysis of variance investigation on the Freeway speeds.

Speed Comparisons at Each Position Under All Ramp Conditions

When considering all of the ramp conditions together as shown in Figure 9, the speeds at Tenth Street, Fifth Street, and North Avenue were not significantly different from each other. The rank order of the positions from lowest speed to highest speed was Fourteenth Street, North Avenue, Tenth Street, and Fifth Street.

Table 10. Rank Order of Freeway Speeds and Significant Differences of Ramp Conditions

Study Location	Ramp Closed			
	Lowest	2nd Lowest	2nd Highest	Highest
14th Street	14th Street	North Avenue	Normal	10th Street
10th Street	14th Street	North Avenue	10th Street	Normal
5th Street	10th Street	North Avenue	Normal	14th Street
North Avenue	North Avenue	10th Street	14th Street	Normal

Table 11. Rank Order of Freeway Speeds and Significant Differences of Study Positions

Ramp Condition	Lowest	2nd Lowest	2nd Highest	Highest
Normal Operation	14th Street	North Avenue	5th Street	10th Street
14th Street Closed	14th Street	10th Street	North Avenue	5th Street
10th Street Closed	North Avenue	14th Street	5th Street	10th Street
North Avenue Closed	North Avenue	14th Street	10th Street	5th Street

Speed Comparisons Under Each Ramp Condition at All Positions

When considering all of the positions together as shown in Figure 9, the speeds under normal operation and with the Tenth Street Southbound Off-Ramp closed were not significantly different from each other. The rank order from lowest speed to highest speed was Fourteenth Street Off-Ramp closed, North Avenue Off-Ramp closed, normal operation, and Tenth Street Off-Ramp closed.

Lane Speeds at a Non-Interchange Location

Table 12 shows the rank order and significant differences of the lane speeds which occurred at Fifth Street. Those ramp conditions which are underlined together have no significant differences and they may be considered in any order. Figure 12 shows the average values of the lane speeds which occurred at Fifth Street.

Lane Speeds at Interchange Locations

Studying the speed conditions which existed at Fourteenth Street, Tenth Street, and North Avenue as shown in Figures 10, 11, and 13 will give an indication of the effect of ramp closures on speeds at interchange locations. Tables 13, 14, and 15 show the rank order and significant differences of ramp conditions for each lane at Fourteenth Street, Tenth Street and North Avenue, respectively.

Tables 13 and 14 show that the speeds in each lane at Fourteenth Street and Tenth Street, respectively were significantly lowest when the Fourteenth Street Southbound Off-Ramp was closed in five of the six cases. These data are substantiated by Table 23.

It can be seen from Table 15 that the speeds in each lane at North Avenue were always significantly lowest where the North Avenue Southbound Off-Ramp was closed. These data are substantiated by Table 23.

Freeway Densities

Density Comparisons at Each Position Under Each Ramp Condition

The densities which were obtained for each ramp condition and position are shown in Figures 8 and 9. One can see that the density generally decreased as the volume decreased in the direction of travel along the

Table 12. Rank Order of Freeway Lane Speeds and Significant Differences of Ramp Conditions at Fifth Street

Lane	Ramp Closed			
	Lowest	2nd Lowest	2nd Highest	Highest
1	10th Street	Normal	14th Street	North Avenue
2	10th Street	North Avenue	14th Street	Normal
3	North Avenue	Normal	10th Street	14th Street

Table 13. Rank Order of Freeway Lane Speeds and Significant Differences of Ramp Conditions at Fourteenth Street

Lane	Ramp Closed			
	Lowest	2nd Lowest	2nd Highest	Highest
1	14th Street	North Avenue	Normal	10th Street
2	14th Street	North Avenue	Normal	10th Street
3	14th Street	North Avenue	Normal	10th Street

Table 14. Rank Order of Freeway Lane Speeds and Significant Differences of Ramp Conditions at Tenth Street

Lane	Ramp Closed			
	Lowest	2nd Lowest	2nd Highest	Highest
1	14th Street	10th Street	North Avenue	Normal
2	14th Street	North Avenue	10th Street	Normal
3	14th Street	North Avenue	10th Street	Normal

Table 15. Rank Order of Freeway Lane Speeds and Significant Differences of Ramp Conditions at North Avenue

Lane	Ramp Closed			
	Lowest	2nd Lowest	2nd Highest	Highest
1	North Avenue	10th Street	14th Street	Normal
2	North Avenue	14th Street	10th Street	Normal
3	North Avenue	10th Street	14th Street	Normal

Freeway. It can be noted from Figure 8 that the density was least uniform when the Fourteenth Street and the North Avenue Southbound Off-Ramps were closed. From this figure, it can be seen also that the most uniform densities occurred when the Tenth Street Southbound Off-Ramp was closed.

Tables 16 and 17 show the rank order and significant differences of the densities at each of the study positions on the Freeway under each ramp condition. It can be noted from these tables that the differences were all insignificant except at Fourteenth Street, where some significant differences were noted. These data are further substantiated by Table 24.

Table 35 shows the results of the analysis of variance investigation on the Freeway densities.

Density Comparisons at Each Position Under All Ramp Conditions

When considering all of the ramp conditions together as shown in Figure 9, the densities at Tenth Street, Fifth Street, and North Avenue were not significantly different from each other. The rank order of the positions from lowest density to highest density was Fifth Street, Tenth Street, North Avenue, and Fourteenth Street.

Density Comparisons Under Each Ramp Condition at All Positions

When considering all of the positions together as shown in Figure 9, the densities under normal operation and with the North Avenue Southbound Off-Ramp closed were not significantly different from each other. The densities obtained with the Tenth Street and the North Avenue Southbound Off-Ramps closed were not significantly different from each other. The rank order from lowest density to highest density was Tenth Street Off-Ramp closed, North Avenue Off-Ramp closed, normal operation, and Fourteenth Street Off-Ramp closed.

Table 16. Rank Order of Freeway Densities and Significant Differences of Ramp Conditions

Study Location	Ramp Closed			
	Lowest	2nd Lowest	2nd Highest	Highest
14th Street	10th Street	North Avenue	Normal	14th Street
10th Street	North Avenue	10th Street	Normal	14th Street
5th Street	14th Street	North Avenue	Normal	10th Street
North Avenue	14th Street	Normal	10th Street	North Avenue

Table 17. Rank Order of Freeway Densities and Significant Differences of Study Positions

Ramp Condition	Lowest	2nd Lowest	2nd Highest	Highest
Normal Operation	North Avenue	5th Street	10th Street	14th Street
14th Street Closed	5th Street	North Avenue	10th Street	14th Street
10th Street Closed	10th Street	14th Street	5th Street	North Avenue
North Avenue Closed	10th Street	5th Street	North Avenue	14th Street

Lane Densities at a Non-Interchange Location

Table 18 shows the rank order and significant differences of the lane densities which occurred at Fifth Street. Those ramp conditions which had no significant differences have again been underlined together and they may be considered in any order. Figure 12 shows the average densities which occurred at Fifth Street.

Lane Densities at Interchange Locations

Studying the density conditions which existed at Fourteenth Street, Tenth Street, and North Avenue as shown in Figures 10, 11, and 13 will give an indication of what effect ramp spacing had on densities at interchange locations. Tables 19, 20, and 21 show the rank order and significant differences of ramp conditions for each lane at Fourteenth Street, Tenth Street, and North Avenue, respectively.

At Fourteenth Street, the significantly highest densities occurred in each lane with the Fourteenth Street Southbound Off-Ramp closed, as shown in Table 19. The least uniform densities occurred in lane one at each of the three interchange locations as may be seen in Tables 19, 20, and 21.

Speed and Delay Studies

Overall Travel and Running Speed

The overall travel and running speeds which occurred on the North Freeway for each ramp condition are shown in Tables 25 and 27, respectively. The analysis of variance computations for these speeds are shown in Tables 26 and 28, respectively. These data verify the results of the analysis of variance of the speeds computed from the time-lapse movie data.

Table 18. Rank Order of Freeway Lane Densities and Significant Differences of Ramp Conditions at Fifth Street

Lane	Ramp Condition			
	Lowest	2nd Lowest	2nd Highest	Highest
1	North Avenue	14th Street	Normal	10th Street
2	North Avenue	14th Street	Normal	10th Street
3	14th Street	North Avenue	10th Street	Normal

Table 19. Rank Order of Freeway Lane Densities and Significant Differences of Ramp Conditions at Fourteenth Street

Lane	Ramp Closed			
	Lowest	2nd Lowest	2nd Highest	Highest
1	10th Street	North Avenue	Normal	14th Street
2	10th Street	Normal	North Avenue	14th Street
3	10th Street	Normal	North Avenue	14th Street

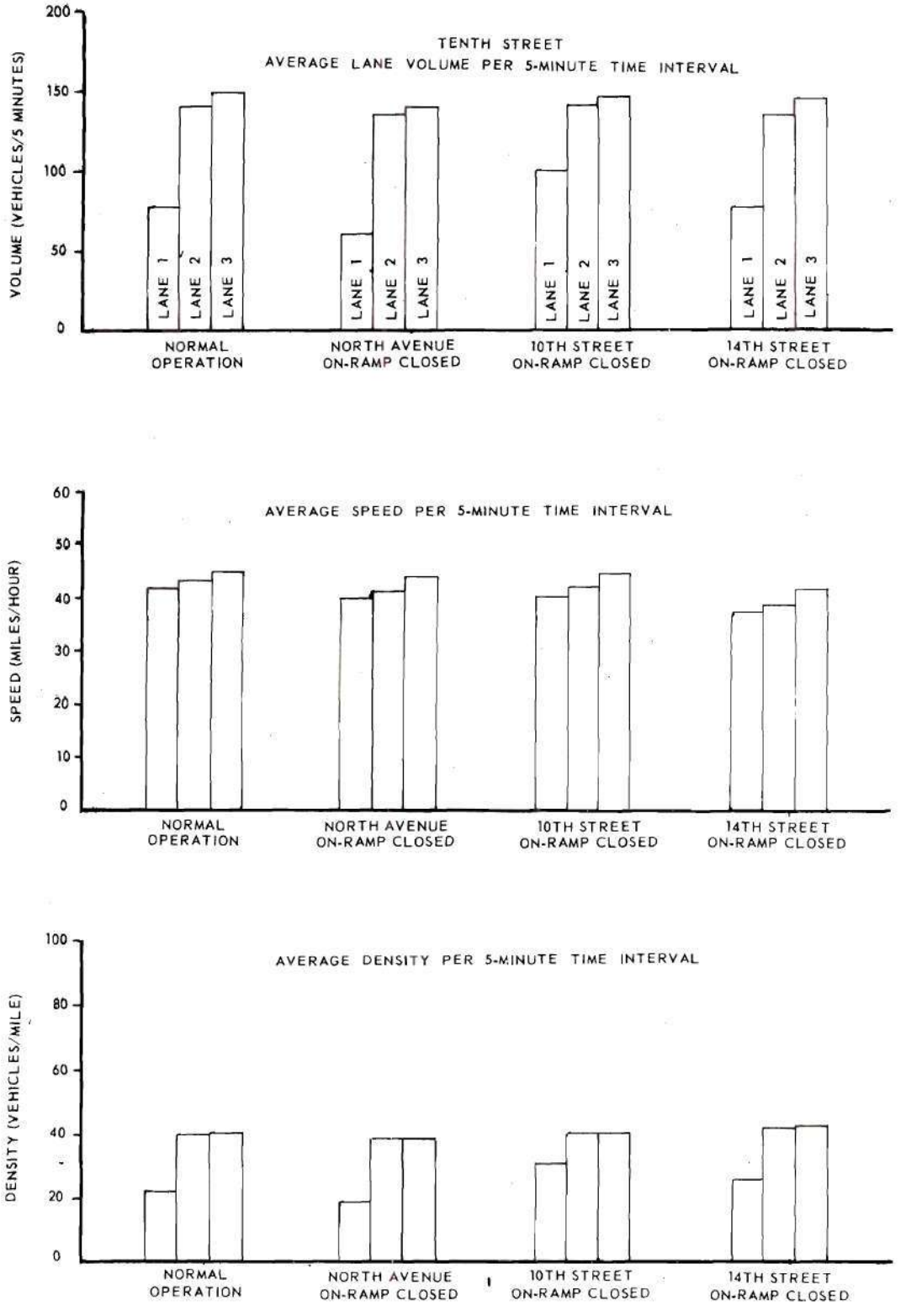

Figure 11. Average Lane Volume, Speed, and Density Per Five-Minute Time Interval on the North Freeway at Tenth Street.

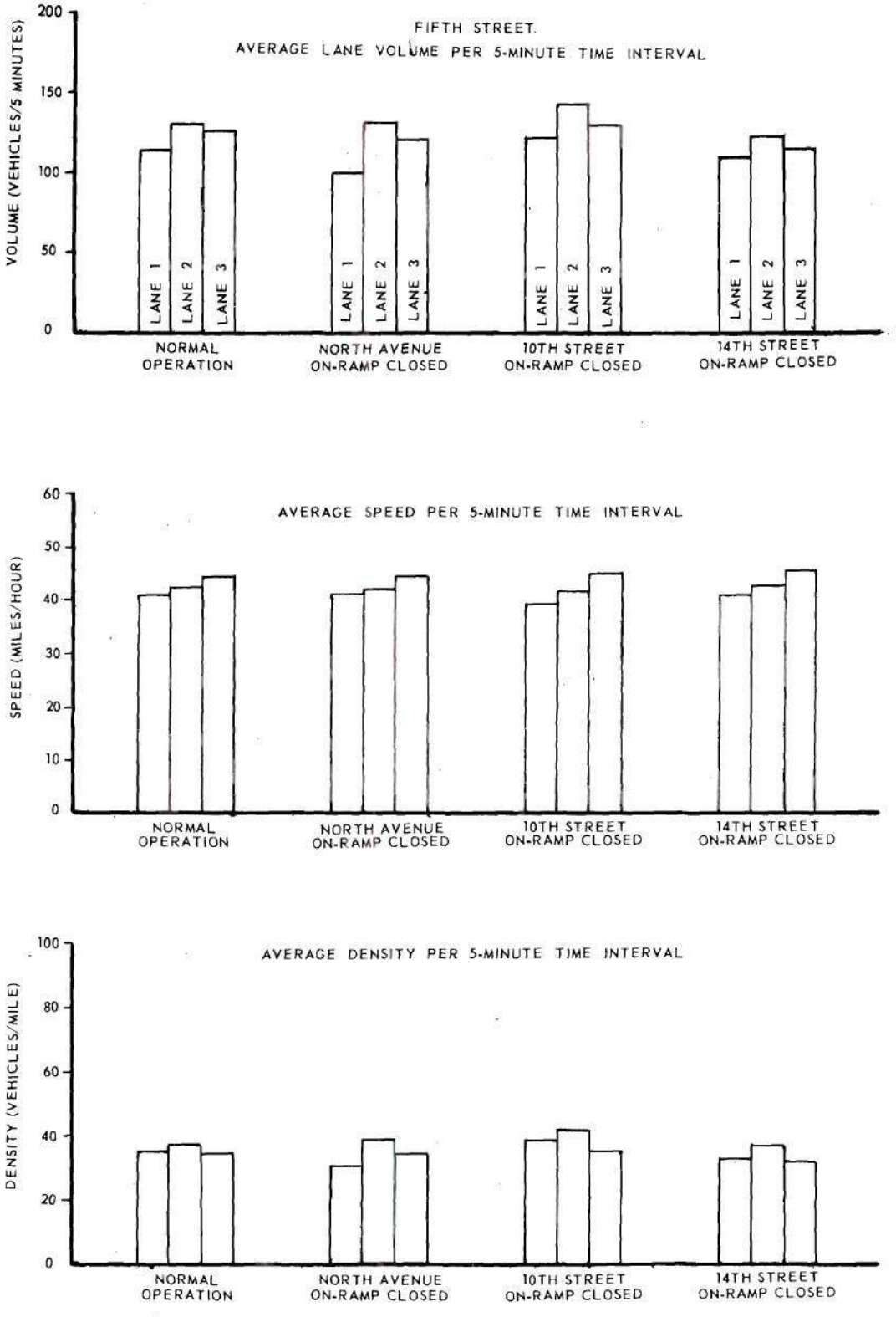

Figure 12. Average Lane Volume, Speed, and Density Per Five-Minute Time Interval on the North Freeway at Fifth Street.

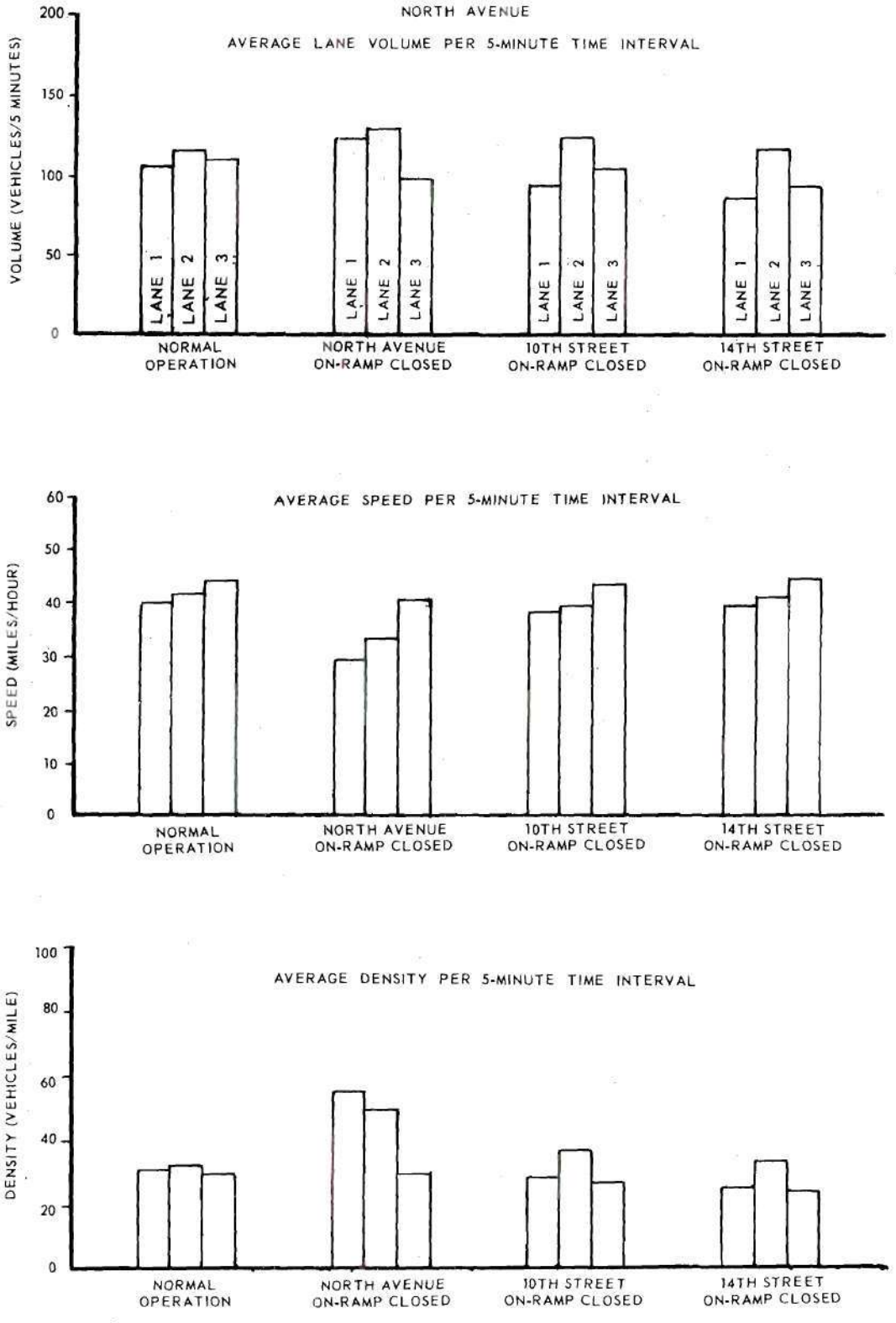

Figure 13. Average Lane Volume, Speed, and Density Per Five-Minute Time Interval on the North Freeway at North Avenue.

Table 20. Rank Order of Freeway Lane Densities and Significant Differences of Ramp Conditions at Tenth Street

Lane	Ramp Closed			
	Lowest	2nd Lowest	2nd Highest	Highest
1	North Avenue	10th Street	Normal	14th Street
2	North Avenue	10th Street	Normal	14th Street
3	North Avenue	10th Street	Normal	14th Street

Table 21. Rank Order of Freeway Lane Densities and Significant Differences of Ramp Conditions at North Avenue

Lane	Ramp Closed			
	Lowest	2nd Lowest	2nd Highest	Highest
1	14th Street	Normal	10th Street	North Avenue
2	10th Street	Normal	14th Street	North Avenue
3	14th Street	10th Street	Normal	North Avenue

The results of the analysis of variance of the overall travel and running speeds on the North Freeway were similar and show that there were no significant differences in the speeds under normal operation or with the Tenth Street Southbound Off-Ramp closed. The speeds tended to be highest under normal operation.

Overall Travel Time

The total travel time expressed in vehicle-minutes which occurred on the North Freeway for each of the ramp conditions is shown in Table 29. The analysis of variance of these travel times is shown in Table 30. The travel time which occurred when the North Avenue Southbound Off-Ramp was closed was significantly different from all the other ramp conditions. The other ramp conditions were not significantly different from each other. The rank order from lowest to highest travel time was Tenth Street Off-Ramp closed, normal operation, Fourteenth Street Off-Ramp closed, and North Avenue Off-Ramp closed.

Travel Distance

The total travel distance expressed in vehicle-miles which occurred on the North Freeway for each of the ramp conditions is shown in Table 31. The analysis of variance of these travel distances may be seen in Table 32. The travel distance was significantly lowest when the Fourteenth Street Southbound Off-Ramp was closed, and was significantly highest when the Freeway was operating under normal conditions. The rank order from lowest to highest travel distance was Fourteenth Street Off-Ramp closed, North Avenue Off-Ramp closed, Tenth Street Off-Ramp closed, and normal operation.

CHAPTER V

RESULTS, CONCLUSIONS AND RECOMMENDATIONS

Summary of Results

A summary of the results of the analysis of the data collected in this study can be outlined as follows:

1. Considering all positions, the highest volumes occurred on the North Freeway when the Freeway was operating normally, and these volumes were significantly different from those observed when any of the ramps were closed. The volumes obtained when any of the off-ramps were closed were not significantly different from each other (see page 29).

2. The traffic volumes decreased as one moved southward along the North Freeway from Fourteenth Street to North Avenue. The volumes observed at Tenth Street and Fifth Street were not significantly different from each other (see page 29).

3. The speed on the North Freeway increased significantly between Fourteenth Street and Tenth Street, when considering all ramp conditions, but there were no significant differences in the speeds observed at the other study locations (see page 36).

4. When considering all study positions, the speeds were significantly lowest when the Fourteenth Street Off-Ramp was closed. The highest speeds occurred when the Tenth Street Off-Ramp was closed and under normal operation, they being not significantly different from each other (see page 37).

5. When considering all of the ramp conditions, the density was significantly highest at Fourteenth Street. The densities observed at each of the other study positions were not significantly different from each other (see page 41).

6. The significantly highest densities occurred at all study positions when the Fourteenth Street Off-Ramp was closed (see page 41).

7. The relative relationship of the volumes in the respective three lanes generally remained unchanged under all ramp conditions at all positions (see Figures 10, 11, 12, and 13).

8. The relative relationship of the speeds in the respective three lanes remained unchanged under all ramp conditions at all positions (see Figures 10, 11, 12, and 13).

9. The relative relationships of the densities in the relative three lanes remained unchanged under all ramp conditions at all study positions (see Figures 10, 11, 12, and 13).

10. Closing any one of the off-ramps did not significantly affect the density on the North Freeway at a study location prior to the ramp that was closed (see Figures 10, 11, and 12).

11. The speed and delay studies made on the Freeway verified the results of the data observed from the time-lapse movie studies (see page 43).

12. Closing any one of the off-ramps on the Freeway tended to reduce the volume on the Freeway, but closing the Fourteenth Street Off-Ramp and the North Avenue Off-Ramp tended to decrease the speeds and thus increase the densities as well (see Figure 8).

13. The total overall travel time on the Freeway was significantly greatest when the North Avenue Off-Ramp was closed. The travel time which

occurred under the other ramp conditions were not significantly different (see page 46).

14. The total travel distance on the Freeway was lowest when the Fourteenth Street Off-Ramp was closed, and was highest when the Freeway was operating normally (see page 46).

Conclusions

The following conclusions were reached as a result of this study:

1. Studying the volume, speed, and density on a freeway at several different locations simultaneously with variable ramp spacings will give a more reliable indication of the actual traffic flow characteristics which exist on the freeway than will a point study.

2. Closing any one of the southbound off-ramps during the morning peak hour caused little or no improvement in the operating characteristics of the North Freeway. When an appreciable change was noted, it was unsually a reduction in the quality of traffic flow.

3. Of all the ramp closings, the closing of the Tenth Street Southbound Off-Ramp caused the least change in the operating characteristics of the North Freeway.

4. The total overall vehicle-minutes of travel time used by all the vehicles traveling through the freeway system is an effective measure of the level of service existing in a freeway system.

5. The high density which was observed at North Avenue when the North Avenue Southbound Off-Ramp was closed was apparently caused by the close proximity of the next exit, Williams Street.

6. In order for a freeway to efficiently handle the morning peak hour traffic flow into the central city, the off-ramps should be spaced as closely together as possible, consistant with the factors of design discussed on pages 4 and 5 and the ability of the surface street system in the vicinity of the off-ramp to accommodate the traffic flow from the ramp.

Recommendations

The following recommendations are made concerning the operating characteristics of the North Freeway:

1. It is recommended that deceleration lanes be constructed at all southbound off-ramps on the Atlanta North Freeway. This would allow motorists to leave the Freeway at a higher rate of speed. This would result in a higher average speed for lane one, the shoulder lane, and would result in a more uniform distribution of speeds and densities in all three lanes of the Freeway. The addition of deceleration lanes could be accomplished relatively easily and with the procurement of little, if any, additional right-of-way.

2. It is recommended that further studies be conducted to determine the feasibility of the construction of a southbound off-ramp at Fifth Street. This addition may possibly not be warranted at the present time, but as the morning peak hour traffic volumes increase on the North Freeway, it is believed that this off-ramp would relieve part of the traffic load on the Tenth Street Southbound Off-Ramp and the North Avenue Southbound Off-Ramps. These two existing off-ramps may become quite congested in the near future as Atlanta continues to grow.

APPENDIX

Table 22. Average Lane Volume and Average Volume per Lane per Five Minute Time Interval on the North Freeway

Position	Lane	Normal Operation	Off-Ramp Closed		
			Fourteenth Street	Tenth Street	North Avenue
Fourteenth Street	1	117.2	123.5	129.7	146.2
	2	146.9	139.9	143.6	136.5
	3	153.6	150.1	152.7	146.6
	Average	139.2	137.8	142.0	143.1
Tenth Street	1	143.9	148.0	103.6	130.2
	2	140.5	133.4	138.0	133.8
	3	151.4	143.9	143.9	138.6
	Average	145.3	141.8	128.5	134.2
Fifth Street	1	116.5	109.4	122.8	100.2
	2	130.0	124.1	142.3	132.6
	3	124.7	116.3	129.8	122.2
	Average	123.6	116.4	131.6	118.3
North Avenue	1	153.4	128.7	110.0	121.4
	2	114.5	116.1	119.8	128.3
	3	109.8	92.2	103.3	96.6
	Average	125.9	112.3	111.0	115.4

Table 23. Average Lane Speed and Average Speed per Lane per Five Minute Time Interval on the North Freeway

Position	Lane	Normal Operation	Off-Ramp Closed		
			Fourteenth Street	Tenth Street	North Avenue
Fourteenth Street	1	37.4	25.0	41.3	35.1
	2	38.5	25.2	40.0	35.1
	3	39.2	27.9	40.6	37.4
	Average	38.4	26.0	40.7	35.9
Tenth Street	1	41.5	37.3	39.9	40.1
	2	42.1	38.9	41.7	40.9
	3	44.4	40.9	44.2	43.6
	Average	42.7	39.1	42.0	41.5
Fifth Street	1	40.3	40.8	38.6	40.9
	2	42.6	42.2	41.1	42.1
	3	44.7	45.3	44.8	44.3
	Average	42.6	42.8	41.5	42.4
North Avenue	1	40.2	39.4	38.3	29.5
	2	41.6	39.4	39.6	33.2
	3	44.3	44.1	43.4	40.4
	Average	42.1	41.0	40.4	34.4

Table 24. Average Lane Density and Average Density per Lane per Five Minute Time Interval on the North Freeway

Position	Lane	Normal Operation	Off-Ramp Closed: Fourteenth Street	Off-Ramp Closed: Tenth Street	Off-Ramp Closed: North Avenue
Fourteenth Street	1	44.9	64.5	21.6	41.0
	2	49.6	67.2	43.3	50.0
	3	48.1	68.6	45.3	49.4
	Average	49.2	66.8	36.8	46.8
Tenth Street	1	41.7	47.7	29.9	18.5
	2	40.0	41.6	40.0	39.6
	3	41.1	42.3	39.2	38.5
	Average	40.9	43.9	36.3	32.2
Fifth Street	1	35.5	32.3	36.1	29.6
	2	36.6	35.5	42.7	35.4
	3	38.6	30.9	34.8	33.6
	Average	36.9	32.9	38.2	32.9
North Avenue	1	46.0	39.3	50.5	55.5
	2	33.0	36.0	27.5	49.8
	3	29.8	25.1	28.7	30.3
	Average	36.3	33.5	38.9	45.2

Table 25. Overall Travel Speed on North Freeway

Day	Replication	Travel Speed (Miles per Hour) Normal Operation	Fourteenth Street Off-Ramp Closed	Tenth Street Off-Ramp Closed	North Avenue Off-Ramp Closed
1	1	25.9	39.6	32.0	23.7
	2	27.6	28.0	37.7	14.0
2	1	22.8	24.4	37.7	17.7
	2	33.9	24.2	22.6	17.1
3	1	36.5	23.7	26.6	16.0
	2	41.5	26.4	25.4	20.2
Mean		31.4	26.1	30.3	18.1

Table 26. Analysis of Variance of Overall Travel Speed on North Freeway

Source of Variance	Sum of Squares	Degrees of Freedom	Mean Square	F Ratio	F Tests $F_{0.20}$	F Tests $F_{0.10}$
Day	24.39	2	12.19	0.5	1.98	2.81
Day-Ramp	256.75	6	42.79	1.92	1.80	2.33
Replication	267.51	12	22.29			
Ramp	6,531.14	3	217.71	5.09	2.29	3.29
Day-Ramp	256.75	6	42.79			

Table 27. Overall Running Speed on North Freeway

Day	Replication	Running Speed (Miles per Hour) Normal Operation	Fourteenth Street Off-Ramp Closed	Tenth Street Off-Ramp Closed	North Avenue Off-Ramp Closed
1	1	26.7	29.6	32.0	25.8
	2	29.9	28.0	37.7	14.3
2	1	27.4	25.6	37.7	18.5
	2	33.9	25.1	24.7	17.8
3	1	36.5	23.7	26.6	20.9
	2	41.5	33.7	28.4	21.8
Mean		32.7	27.6	31.2	19.9

Table 28. Analysis of Variance of Overall Running Speed on North Freeway

Source of Variance	Sum of Squares	Degrees of Freedom	Mean Square	F Ratio	F Tests $F_{0.20}$	F Tests $F_{0.10}$
Day	31.73	2	15.86	0.7	1.98	2.81
Day-Ramp	174.57	6	29.09	1.35	1.80	2.33
Replication	259.29	12	21.61			
Ramp	589.22	3	196.41	7.63	2.09	2.92
DR + Day	206.30	8	25.79			

Table 29. Total Overall Travel Time on North Freeway

Day	Replication	Travel Time (Vehicle-Minutes) Normal Operation	Fourteenth Street Off-Ramp Closed	Tenth Street Off-Ramp Closed	North Avenue Off-Ramp Closed
1	1	28,701	21,483	19,854	34,504
	2	25,095	22,189	17,141	30,519
2	1	23,539	23,286	23,660	39,116
	2	16,180	24,889	26,329	27,140
3	1	18,998	26,245	17,025	44,208
	2	16,075	22,832	23,655	37,694
Mean		21,431	23,487	21,244	35,530

Table 30. Analysis of Variance of Total Overall Travel Time on North Freeway

Source of Variance	Sum of Squares	Degrees of Freedom	Mean Square	F Ratio	F Tests $F_{0.20}$	$F_{0.10}$
Day	3,369,940	2	1,684,970	0.1	1.98	2.81
Day-Ramp	233,446,970	6	38,907,829	2.80	1.80	2.33
Replication	175,298,230	12	14,608,185			
Ramp	834,127,700	3	278,042,560	7.15	2.29	3.29
Day-Ramp	233,446,970	6	38,907,829			

Table 31. Total Travel Distance on North Freeway

Day	Replication	Travel Distance (Vehicle-Miles) Normal Operation	Fourteenth Street Off-Ramp Closed	Tenth Street Off-Ramp Closed	North Avenue Off-Ramp Closed
1	1	11,221	10,162	10,595	10,371
	2	11,291	10,299	11,000	10,473
2	1	11,438	9,836	10,644	10,891
	2	10,723	10,475	10,580	10,937
3	1	10,951	10,524	10,857	10,627
	2	11,134	10,507	10,575	10,724
Mean		11,126	10,301	10,709	10,671

Table 32. Analysis of Variance of Total Travel Distance on North Freeway

Source of Variance	Sum of Squares	Degrees of Freedom	Mean Square	F Ratio	F Tests $F_{0.20}$	$F_{0.10}$
Day	16,264.1	2	8,132.0	0.2	1.98	2.81
Day-Ramp	456,638.2	6	76,106.4	1.47	1.80	2.33
Replication	623,283.4	12	51,940.3			
Ramp	2,053,765.8	3	684,588.6	11.6	2.09	2.92
DR + Day	472,902.3	8	59,112.8			

Table 33. Analysis of Variance of Volume on the North Freeway

Source	Sum of Squares	Degrees of Freedom	Mean Square	F	F Tests $F_{0.20}$	F Tests $F_{0.10}$
Day	747.3	1	747.3	4.550	1.784	2.706
RD	1146.9	3	382.3	2.328	1.608	2.084
PD	422.1	3	140.7	0.857	1.608	2.084
LD	319.8	2	159.9	0.974	1.692	2.303
PRD	820.5	9	91.2	0.555	1.387	1.632
RLD	347.4	6	57.9	0.352	1.463	1.774
PLD	671.4	6	111.9	0.681	1.463	1.774
PRLD	3708.1	18	206.0	1.254	1.268	1.421
T(PRLD)	141901.7	864	164.2			
Lane	1525.4	2	762.7	4.769	5.000	9.000
LD	319.8	2	159.9			
Position	85633.1	3	28544.4	202.868	3.367	5.391
PD	422.1	3	140.7			
Ramp	13869.5	3	4623.2	12.093	3.367	5.391
RD	1146.9	3	382.3			
PRL	35851.3	18	1991.7	9.668	1.530	1.837
PRLD	3708.1	18	206.0			
PL	95334.1	6	15889.0	141.999	2.206	3.055
PLD	671.4	6	111.9			
RL	7969.3	6	1328.2	22.942	2.206	3.055
RLD	347.4	6	57.9			
PR	21970.9	9	2441.2	26.776	1.874	2.440
PRD	820.6	9	91.2			
Total	412238.8	959				

Table 34. Analysis of Variance of Speed on the North Freeway

Source	Sum of Squares	Degrees of Freedom	Mean Square	F	F Tests $F_{0.20}$	F Tests $F_{0.10}$
Day	35.9	1	35.9	2.357	1.784	2.706
RD	67.1	3	22.3	1.467	1.608	2.084
PD	432.4	3	144.1	9.459	1.608	2.084
LD	3.3	2	1.7	0.110	1.692	2.303
PRD	1753.7	9	194.9	12.788	1.387	1.632
RLD	61.0	6	10.2	0.668	1.463	1.774
PLD	84.1	6	14.0	0.920	1.463	1.774
PRLD	158.2	18	8.8	0.577	1.268	1.421
T(PRLD)	13164.9	864	15.2			
Lane	2693.2	2	1346.6	804.400	5.000	9.000
LD	3.3	2	1.70			
Position	7324.6	3	2441.5	16.940	3.367	5.391
PD	432.4	3	144.1			
Ramp	2698.7	3	899.6	40.250	3.367	5.391
RD	67.1	3	22.4			
PRL	382.0	18	21.2	2.415	1.530	1.837
PRLD	158.2	18	8.8			
PL	469.4	6	78.2	5.578	2.206	3.055
PLD	84.1	6	14.0			
RL	72.4	6	12.1	1.186	2.206	3.055
RLD	61.0	6	10.2			
PR	7110.7	9	790.1	4.055	1.874	2.441
PRD	1753.7	9	194.9			
Total	36511.6	959				

Table 35. Analysis of Variance of Density on the North Freeway

Source	Sum of Squares	Degrees of Freedom	Mean Square	F	F Tests $F_{0.20}$	F Tests $F_{0.10}$
Day	206.8	1	206.8	2.666	1.784	2.706
RD	184.7	3	61.6	0.794	1.608	2.084
PD	1887.4	3	629.1	8.109	1.608	2.084
LD	139.5	2	69.7	8.987	1.692	2.303
PRD	5040.9	9	560.1	7.219	1.387	1.632
RLD	383.4	6	63.9	0.824	1.463	1.774
PLD	1377.4	6	229.6	2.950	1.463	1.774
PRLD	1742.9	18	96.8	1.248	1.268	1.421
T(PRLD)	67038.0	864	77.60			
Lane	3993.2	2	1996.6	28.634	5.000	9.000
LD	139.5	2	67.9			
Position	42917.3	3	14305.8	22.738	3.367	5.391
PD	1887.4	3	629.1			
Ramp	3944.0	3	1314.7	21.353	3.367	5.391
RD	184.7	3	61.6			
PRL	4306.5	18	239.3	2.471	1.530	1.837
PRLD	1742.9	18	96.8			
PL	11719.0	6	1953.2	8.508	2.206	3.055
PLD	1377.4	6	229.6			
RL	1202.7	6	200.4	3.137	2.206	3.055
RLD	383.4	6	63.9			
PR	23102.7	9	2567.0	4.583	1.874	2.440
PRD	5040.9	9	560.1			
Total	169186.6	959				

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